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(54) **SCALABLE STORAGE PROTECTION**

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***G11B 20/18*** (2006.01)
***G06F 3/06*** (2006.01)
*G06F 11/10* (2006.01)

(52) **U.S. Cl.**
CPC .......... ***G11B 20/1803*** (2013.01); ***G06F 3/065*** (2013.01); ***G06F 3/067*** (2013.01); ***G06F 3/0613*** (2013.01); ***G06F 3/0619*** (2013.01); ***G06F 3/0689*** (2013.01); *G06F 11/1076* (2013.01); *G06F 2211/1028* (2013.01)

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CPC ........ G06F 3/0607; G06F 8/65; G06F 3/0608; G06F 3/0674; G06F 3/0689
USPC ........................................................ 714/6.32
See application file for complete search history.

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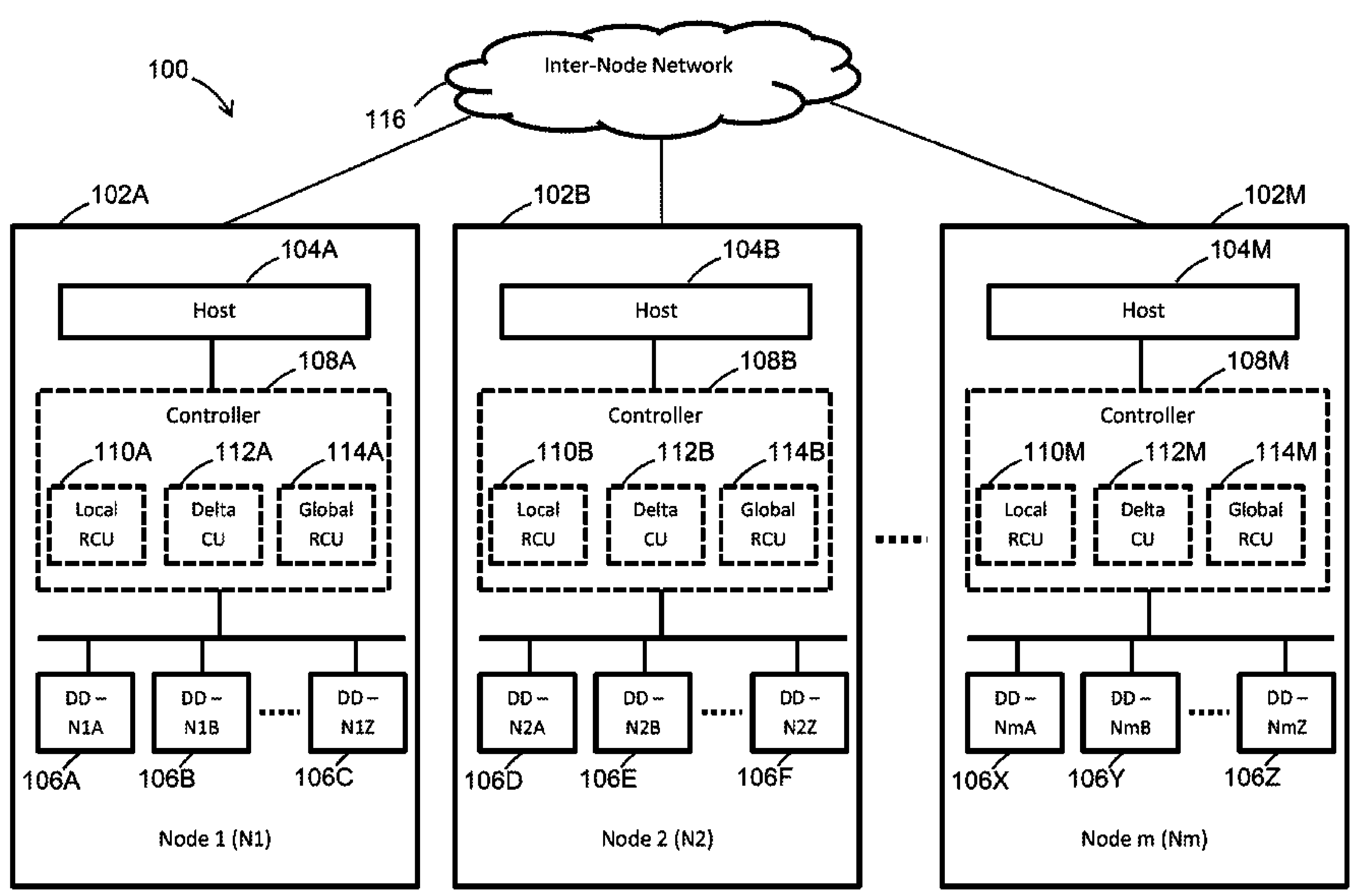
(57) **ABSTRACT**

The disclosure is directed to protecting data of a scalable storage system. A scalable storage system includes a plurality of nodes, each of the nodes having directly-attached storage (DAS), such as one or more hard-disk drives and/or solid-state disk drives. The nodes are coupled via an inter-node communication network, and a substantial entirety of the DAS is globally accessible by each of the nodes. The DAS is protected utilizing intra-node protection to keep data stored in the DAS reliable and globally accessible in presence of a failure within one of the nodes. The DAS is further protected utilizing inter-node protection to keep data stored in the DAS reliable and globally accessible if at least one of the nodes fails.

**21 Claims, 3 Drawing Sheets**



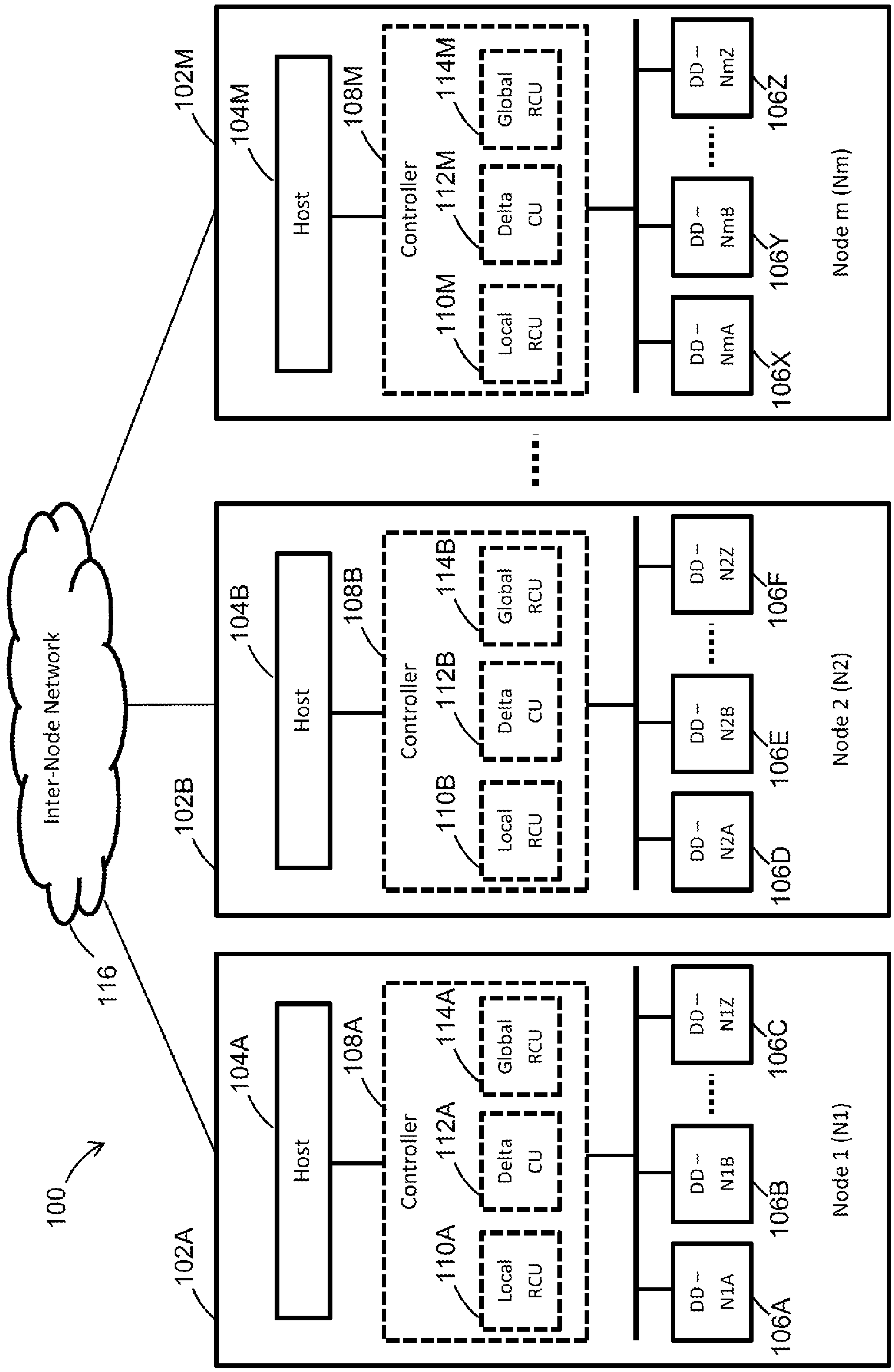

100
116
Inter-Node Network
102A
104A
Host
108A
Controller
110A
Local RCU
112A
Delta CU
114A
Global RCU
DD – N1A
DD – N1B
DD – N1Z
106A
106B
106C
Node 1 (N1)
102B
104B
Host
108B
Controller
110B
Local RCU
112B
Delta CU
114B
Global RCU
DD – N2A
DD – N2B
DD – N2Z
106D
106E
106F
Node 2 (N2)
102M
104M
Host
108M
Controller
110M
Local RCU
112M
Delta CU
114M
Global RCU
DD – NmA
DD – NmB
DD – NmZ
106X
106Y
106Z
Node m (Nm)

FIG. 1

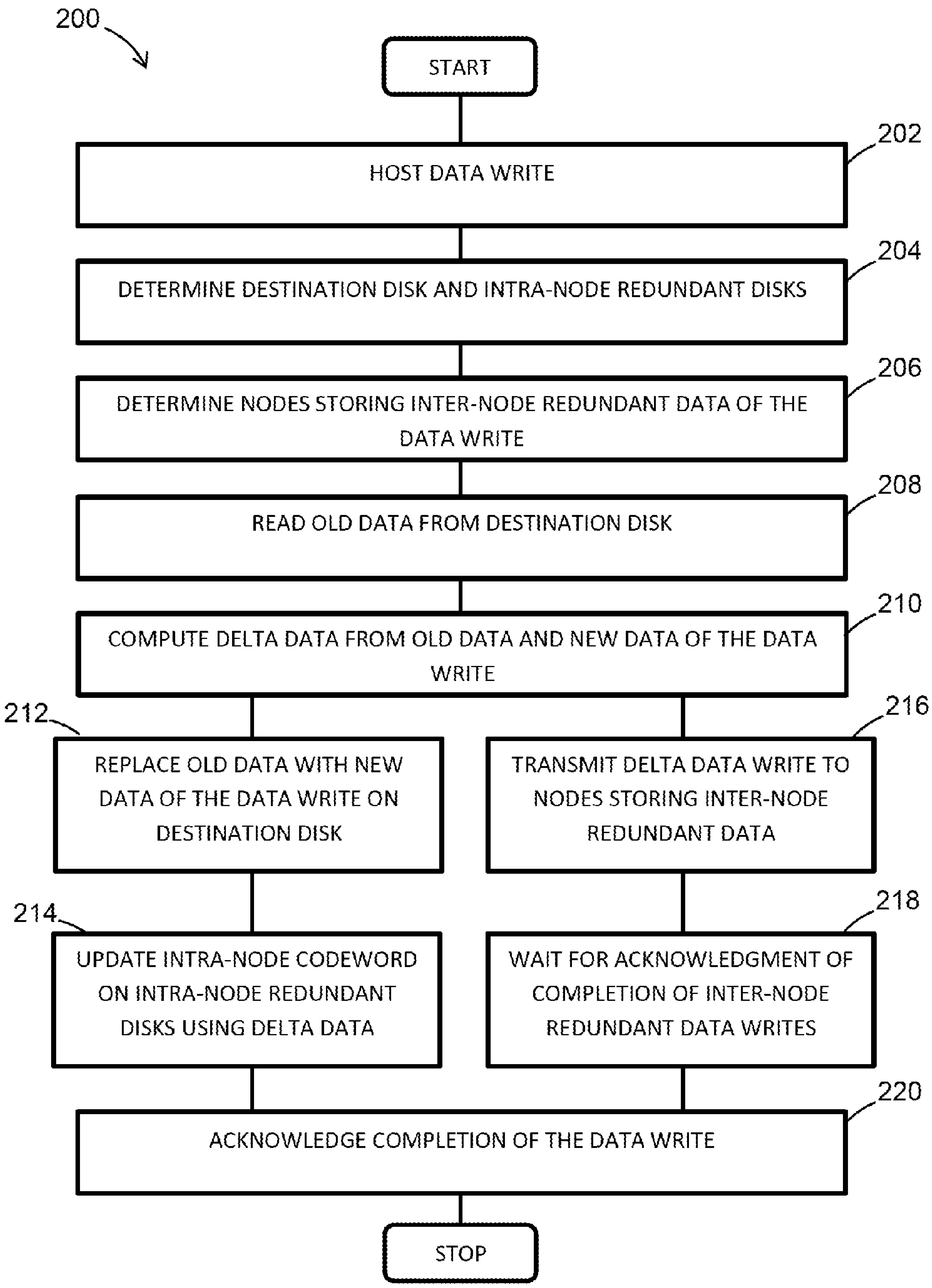

200
START
202
HOST DATA WRITE
204
DETERMINE DESTINATION DISK AND INTRA-NODE REDUNDANT DISKS
206
DETERMINE NODES STORING INTER-NODE REDUNDANT DATA OF THE DATA WRITE
208
READ OLD DATA FROM DESTINATION DISK
210
COMPUTE DELTA DATA FROM OLD DATA AND NEW DATA OF THE DATA WRITE
212
REPLACE OLD DATA WITH NEW DATA OF THE DATA WRITE ON DESTINATION DISK
216
TRANSMIT DELTA DATA WRITE TO NODES STORING INTER-NODE REDUNDANT DATA
214
UPDATE INTRA-NODE CODEWORD ON INTRA-NODE REDUNDANT DISKS USING DELTA DATA
218
WAIT FOR ACKNOWLEDGMENT OF COMPLETION OF INTER-NODE REDUNDANT DATA WRITES
220
ACKNOWLEDGE COMPLETION OF THE DATA WRITE
STOP

FIG. 2

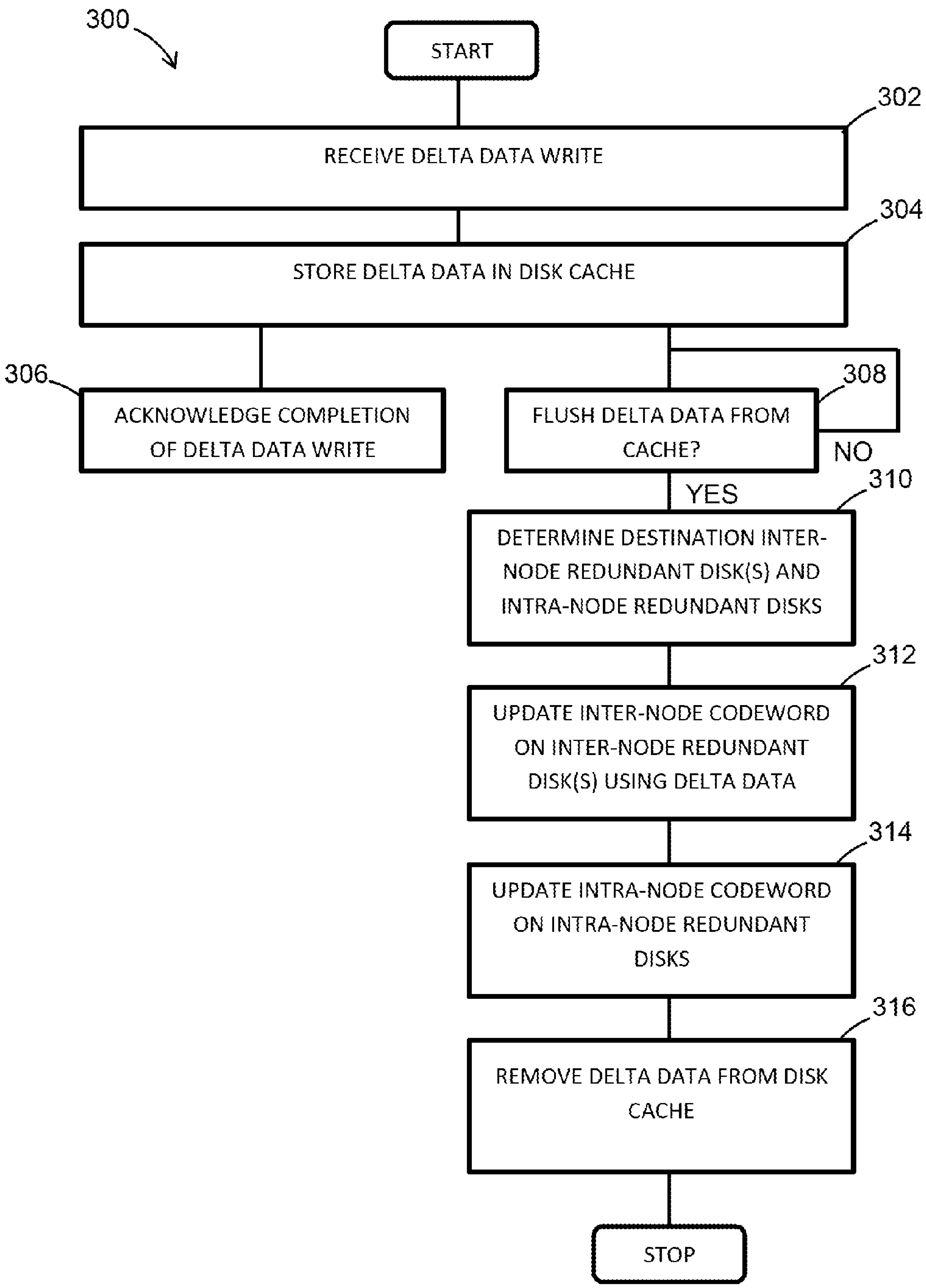

300
START
302
RECEIVE DELTA DATA WRITE
304
STORE DELTA DATA IN DISK CACHE
306
ACKNOWLEDGE COMPLETION OF DELTA DATA WRITE
308
FLUSH DELTA DATA FROM CACHE?
NO
YES
310
DETERMINE DESTINATION INTER-NODE REDUNDANT DISK(S) AND INTRA-NODE REDUNDANT DISKS
312
UPDATE INTER-NODE CODEWORD ON INTER-NODE REDUNDANT DISK(S) USING DELTA DATA
314
UPDATE INTRA-NODE CODEWORD ON INTRA-NODE REDUNDANT DISKS
316
REMOVE DELTA DATA FROM DISK CACHE
STOP

FIG. 3

# SCALABLE STORAGE PROTECTION

## PRIORITY

The present application claims priority to U.S. Provisional Application Ser. No. 61/696,720, entitled SCALABLE STORAGE PROTECTION, By Earl Cohen et al., filed Sep. 4, 2012, which is currently co-pending, or is an application of which a currently co-pending application is entitled to the benefit of the filing date.

## BACKGROUND

Scalable storage systems with directly attached disks require redundancy mechanisms for data protection. Within a single node, such as a single server, various techniques are used for protection of directly-attached storage (DAS), such as RAID-5, RAID-6, other RAID levels, or variations thereof. In distributed systems or in large-scale storage systems, such as large JBOD complexes, erasure-coding techniques are used to provide protection by distributing error-correction coding over a larger number of disks. Erasure-coding, however, requires shipping (i.e. sending and receiving) large amounts of data. In some embodiments, data must be updated at r separate disks to handle r out of n drive failures. When combined with resiliency against node failures, the foregoing systems tend to become very expensive in an amount of redundancy and/or in an amount of data that must be shipped between nodes for updating or for recovery.

## SUMMARY

An embodiment of the disclosure is directed to a storage system including a plurality of processing nodes in communication with one another. Each processing node includes a plurality of disks in communication with at least one host. The host is configured for writing data to a selected disk of the plurality of disks. A local redundancy computation unit is configured for determining local redundant data utilizing data written to the selected disk by the host. The local redundancy computation unit is further configured for storing local redundant data on at least one disk of the plurality of disks. A delta computation unit is configured for determining delta data utilizing data written to the selected disk by the host. The delta computation unit is further configured for sending delta data to at least one other processing node. A global redundancy computation unit is configured for receiving delta data from at least one other processing node. The global redundancy computation unit is further configured for determining global redundant data utilizing delta data received from the other processing node and storing global redundant data on at least one disk of the plurality of disks.

It is to be understood that both the foregoing general description and the following detailed description are not necessarily restrictive of the disclosure. The accompanying drawings, which are incorporated in and constitute a part of the specification, illustrate embodiments of the disclosure.

## BRIEF DESCRIPTION OF THE DRAWINGS

The embodiments of the disclosure may be better understood by those skilled in the art by reference to the accompanying figures in which:



FIG. **1** is a block diagram illustrating a scalable storage system, in accordance with an embodiment of the disclosure;

FIG. **2** is a flow diagram illustrating a method of processing a host data write, in accordance with an embodiment of the disclosure; and

FIG. **3** is a flow diagram illustrating a method of processing delta data, in accordance with an embodiment of the disclosure.

## DETAILED DESCRIPTION

Reference will now be made in detail to the embodiments disclosed, which are illustrated in the accompanying drawings.

FIGS. **1** through **3** generally illustrate embodiments of a system and method for protecting at least one scalable storage system. Some challenges in scalable storage systems include providing a combination of global access to all data, resiliency from disk failures, and mechanisms for handling failures of one or more processing nodes. At least some of the foregoing challenges are accomplished by balancing redundancy at the intra-node level to protect against intra-node failures, such as hard disk drive (HDD) failures, with redundancy at the inter-node level to protect against failures of one or more of the nodes, such as failures of the intra-node protection. In some embodiments, caching at the nodes in a distributed manner further improves local performance of each of the nodes and improves the system-level performance of the scalable storage system by enabling earlier acknowledgements of writes used for data protection.

FIG. **1** illustrates an embodiment of a storage system **100** such as, but not limited to, a scalable directly-attached storage (DAS) system. The system **100** includes a plurality of processing nodes **102**, such as servers. Each of the processing nodes **102** includes respective (i.e. local) host **104** (such as one or more processors or CPUs), and respective (i.e. local) DAS **106**, such as a plurality of disk drives **106**. In various embodiments, the local DAS **106** are communicatively coupled to the local host **104** via one or more respective (i.e. local) I/O controllers **108**. A substantial entirety, such as all, of the storage **106**A-**106**Z is globally visible to all of the processing nodes **102**. The DAS **106**A-**106**C of a particular processing node **102**A is termed the respective "local storage" of the particular processing node **102**A. DAS **106**D-**106**Z of other processing nodes **102**B-**102**M is termed the respective "foreign storage" of the particular processing node **102**A. The processing nodes **102** are in communication with one another via an inter-node communication network **116** such as, but not limited to, a serial attached small computer system interface (SAS) switching interconnect. The processing nodes **102** have access to the substantial entirety of the storage **106**A-**106**Z through the inter-node communication network **116**. In some embodiments, however, access to the respective local storage **106**A-**106**C of a particular processing node **102**A is quicker and/or higher in bandwidth than access to the respective foreign storage **106**D-**106**Z. In some embodiments, the inter-node communication network **116** includes, but is not limited to, at least one SAS fabric, Ethernet network, InfiniBand network, peripheral component interconnect express (PCIe) interconnect network, Local Area Network (LAN), Wide Area Network (WAN), proprietary network, or any combination of the foregoing.

In some embodiments, the system **100** further includes locking and/or coherency mechanisms to facilitate sharing of the storage **106**. For example, a directory-based caching mechanism enables tracking ownership and/or modification of data. In some embodiments, each of the processing nodes **102** includes a cache, such as a disk cache, to store frequently accessed data. According to various embodiments, some of the frequently-accessed data is local to the processing node and/or some of the frequently-accessed data is foreign. In some embodiments, the disk cache includes, but is not limited to, a solid-state disk drive (SSD).

Some failure scenarios of concern in multi-node storage systems **100**, include:

- Failure of one or more input/output (I/O) devices, such as HDDs or SSDs **106** of a processing node **102**;
- Failure of a pathway to one or more of the I/O devices **106** within one of the processing nodes **102**;
- Failure of some or all of a processing node **102**, such as a host **104** or intra-node communication infrastructure; and
- Failure of higher-level communication infrastructure, such as the inter-node communication network **116**, coupling the processing nodes **102**.

These failures are categorized as intra-node or inter-node failures. An intra-node failure is one that renders at least a portion of a processing node **102** unusable but does not prevent continued operation of the processing node **102**, including global access to data that is local to the processing node **102**. An inter-node failure is one that renders a processing node **102** or at least a portion of data that is local to the processing node **102** unusable. Some intra-node failures are fixable at a level of the affected processing node **102**, and are not globally visible to other processing nodes **102** (except for possible performance impacts).

Failures are also characterized as hard (e.g. solid, repeatable) or as soft (e.g. one-time, transient, goes away after a power-cycle). Many node failures are soft, such as software crashing, and are thus transient or short in duration. Disk failures are also either soft (e.g. a transient, uncorrectable error that is recoverable by writing new data) or hard (e.g. failure of the disk due to a head crash). Failure duration, hence hard versus soft failure categorization, is relevant for computing probability of failure based on how many contemporaneous errors of various types are considered. In some embodiments, probability of simultaneously having multiple processing node failures if most processing node failures are soft failures is less than probability of simultaneously having multiple processing node failures if most processing node failures are hard failures.

A system-level failure is a failure of the multi-node storage system **100**, such as an unrecoverable loss of any of the host-written (i.e., non-redundant) data stored on any of the processing nodes **102** or a loss of more than a specified number of the processing nodes **102**. In some embodiments, the system **100** is designed, at least in part, to reduce probability of system-level failure to less than a specified value.

Simple erasure-coding solutions tend to entail a high amount redundancy and/or data shipping. For example, consider m nodes **102**, each including n disks **106** (such as HDDs or SSDs), thus a total of m*n disks **106**. To protect against a failure of any 3 disks **106**, at least three of the disks **106** must include redundant data. Any write to any of the other (m*n−3) data (i.e. non-redundant) disks **106** requires an update of the 3 redundant disks **106**. When a host **104**, such as a processor, performs a small, random write (e.g. 4 KB or 8 KB write) to one of the data disks **106**, four similar-sized writes must be done in total, and three of the four writes involve computations (i.e. updating the redundant data based on old data prior to the host write and new data written by the host). Furthermore, if one or more node failures are to be handled with erasure-coding, the three redundant disks **106** are preferably located on different nodes **102**. Accordingly, the host write requires: reading old data from a selected data disk **106**A of a node **102**A including the selected data disk; replacing old data with new data provided by the host **104** by writing the new data to the selected data disk **106**A; computing a function, such as a delta, between the old data and the new data; shipping the delta to the three redundant disks **106**, which may be located on different nodes **102**; reading an old version of the redundant data on each node **102** that includes one of the redundant disks **106**; determining an update to the redundant data utilizing the delta; and writing back a new version of the redundant data. Shipping the delta to multiple nodes **102** consumes both latency and power. In some embodiments, a further delay occurs because the host write cannot be acknowledged until the host write data is “safe”, and the host write data is not safe until the redundant data writes are complete.

A single protection solution that works well for failures within a node **102**, such as RAID, may not be adequate across a plurality of nodes **102**. A global solution such as erasure-coding, illustrated in the foregoing example, may be too costly in terms of an amount of data that is shipped between nodes **102**. Furthermore, various failure scenarios have different likelihoods. Typically, decreasing probability of system-failure is more important than separately decreasing probability of disk failure or probability of node failure. In some embodiments, the system **100** is configured for achieving one or more of: less data shipped between nodes; higher performance; lower cost (e.g. lowering an amount of redundancy required for a given system-level failure probability); lower power; lower latency; and other power, cost, and performance metrics. For example, failures of individual hard disk drives **106** can be very likely. In some embodiments, therefore, probability of system-failure is decreased by providing more redundancy to protect against hard disk drive failures and less for node failures, thereby decreasing probability of system-failure without overly compromising performance or requiring high data shipping or redundancy costs.

In an embodiment (see FIG. **1**), the system **100** includes a first type of protection (i.e. “inner”, “local”, or “intra-node” protection) to protect data stored in I/O devices **106** within a node **102**, and a second type of protection (i.e. “outer”, “global”, or “inter-node” protection) to protect against failures of one or more nodes **102**. The foregoing scalable storage protection scheme decreases an amount of data that must be shipped between nodes **102** for protection and for recovery. Furthermore, a delta-caching mechanism decreases time required to acknowledge that a host write is safely stored.

In some embodiments, the system **100** includes separate mechanisms **110**, **114** to protect against local (i.e. intra-node) vs. global (i.e. inter-node) failures. In further embodiments, the local protection mechanisms **110** and global protection mechanisms **114** are each selected to reduce a respective failure probability, thereby reducing an overall system-level failure probability to a specified level. In various embodiments, the local protection mechanisms **110** and global protection mechanisms **114** are each selected to reduce an amount of data that is shipped among nodes **102** for redundant data storage and recovery from failures.

In some embodiments, the system **100** with scalable storage protection offers cost advantages. For example, consider the previously described simple, erasure-coding with m nodes **102** each with n disks **106** and a requirement to protect against 3 disk failures, and assuming the redundant disks **102** are all on different nodes **102**. The simple, erasure-coding approach is shipping three times as much data as the write data to other nodes **102** for redundancy. The multiple layer protection offered by the system **100** with scalable storage protection allows flexible balancing. For example, in some embodiments the system **100** is designed based on various failure probabilities (e.g. hard failures versus soft failures) or expense factors (e.g. expense of shipping data).

In an exemplary embodiment of the system **100** with scalable storage protection instead of the simple, erasure-coding approach described above, two of n disks **106** at each of the nodes **102** include redundant local data of that node **102**, and one or more of the m nodes **102** (i.e. redundant nodes) include globally redundant data. In an embodiment with one redundant node **102**, when a host **104** performs a small, random write (e.g. 4 KB or 8 KB write) to one of the data disks **106**, four similar-sized writes must be done in total, but three of the similar-sized writes are local (i.e. the host write data and two local redundant data writes). Only one of the similar-sized writes must be shipped to the redundant node **102**. Compared to the simple, erasure-coding example, the amount of data to be shipped is reduced (e.g. ⅔ as much). In the foregoing example, the system **100** with scalable storage protection is able to handle at least three disk failures. In some embodiments, the system **100** is enabled to handle two disk failures per node **102**.

In the foregoing example, three disk failures on one node **102** is substantially equivalent or similar to failure of a node **102** because the two redundant disks **106** of each node **102** are only able to correct for failures of two of the n disks **106** at the node **102**. In some embodiments, probability of intra-node protection failing is included in probability of the node **102** failing and is utilized, at least in part, to determine a required level of inter-node protection. The simple, erasure-coding approach is able to handle up to three node failures, but a consequence of this is that a higher percentage of the nodes **102** are used to process globally redundant data. If node failure probability is small compared to disk failure probability, the scalable storage protection alternative offers equivalent or better protection at a lower cost in at least one of I/O shipping and redundancy.

The foregoing examples illustrate at least some advantages of the system **100** with scalable storage protection compared to a simple, erasure-coding protected system. However, the examples are not intended to limit the disclosure in any way. According to various embodiments, the system **100** includes any combination of selected parameters and configurations implementing the scalable storage protection scheme generally described herein. In an embodiment, the system **100** includes m nodes **102**, each with n disks **106**. The system **100** is configured to survive k node failures (e.g. k=2). Every group of g disks includes at least h redundant disks **106** to handle disk-level failures adequately (e.g. h=3 out of g=10 disks **106** are redundant).

In some embodiments, g=n by appropriate scaling of h. Accordingly, the system **100** includes m*n total disks **106** and h*m of the disks **106** store redundant data. To survive k of m node failures, the redundant disks **106** in one codeword (e.g. one protection group) are on at least k different nodes **102**. None of the m nodes **102** is able to have more than h*m/k of the redundant disks **106** that are protected by a same codeword. Otherwise, k node failures may not be survivable. In an embodiment, therefore, n is greater than h*m/k or redundant data must be present on more than k of the nodes **102**. For example, if n=10, m=8, h=3, and k=2, then 24 redundant disks **106** out of 80 are required. However, there are only 10 disks **106** per node **102** so the redundant disks must be spread among at least three nodes, even though k is only 2.

Erasure-coding may be able to meet reliability requirements; however, it has a number of deficits including the following. An h of g erasure code is computationally expensive If h is larger than k, then either one node **102** must process multiple erasure code updates (leading to unbalanced computational effort), or required I/O shipping is proportional to h rather than k. If n is less than h*m/k, then I/O shipping is greater than proportional to k. Recovery from even a single disk failure generally requires I/O shipping. Furthermore, system-level performance is typically poor because having at least one failed disk **106** is common and I/O shipping is often required for recovery.

The system **100** with scalable storage protection includes an intra-node protection mechanism **110** using local redundancy to protect against intra-node failures, such as disk failures, and an inter-node protection mechanism **114** using global redundancy to protect against inter-node failures, such as node failures. According to various embodiments, the system **100** offers several advantages including one or more of: I/O shipping is based on a selected number of survivable node failures and is orthogonal to handling of disk failures; hard disk failures are recoverable locally without I/O shipping with up to a specified reliability level being recoverable with intra-node protection; shorter, simpler coding types are used to achieve a specified level of system-failure probability, allowing for more efficient hardware; and other performance, efficiency, and/or scalability advantages.

The intra-node protection mechanism **110** includes one or more coding types, such as one or more of: RAID-1; RAID-2; RAID-3; RAID-4; RAID-5; RAID-6; any other RAID level; an erasure code, such as a Reed-Solomon code, a fountain code, a Raptor code, a rate-less erasure code, or an Online code; and any combination of the foregoing. The inter-node protection mechanism **114** includes one or more coding types, such as one or more of: RAID-1; RAID-2; RAID-3; RAID-4; RAID-5; RAID-6; any other RAID level; an erasure code, such as a Reed-Solomon code, a fountain code, a Raptor code, or an Online code; and any combination of the foregoing.

Data stored on a plurality of disks **106** that is protected by one instance of the intra-node protection mechanism **110** or the inter-node protection mechanism **114** is referred to as a codeword. For example, data stored on five disks, one of which is redundant as in RAID-5, represents one codeword for each separately readable and correctable set of the data. RAID-5 is operable at a byte level, whereas many disks are only able to read 512 B sectors of data, hence in such a case, each codeword would be a number of 512 B sectors, one sector from each of the five disks.

In some embodiments, the intra-node protection mechanism **110** and the inter-node protection mechanism **114** are both configured for a same coding type. For example, in various embodiments, both the intra-node protection mechanism **110** and the inter-node protection mechanism **114** use a two-erasure-correcting code, such as in RAID-6, or both can use a one-erasure-correcting code, such as in RAID-5. In other embodiments, the intra-node protection mechanism **110** and the inter-node protection mechanism **114** use different coding types. For example, in some usage scenarios, the intra-node protection mechanism **110** uses a two-erasure-correcting code and the inter-node protection mechanism **114** uses a one-erasure-correcting code, such as in RAID-5.

Computations of the intra-node protection mechanism **110** and the inter-node protection mechanism **114** are according to a respective coding type. For example, a one-erasure-correcting RAID-5 coding type requires XOR computations, and a RAID-6 coding type requires computations according to a two-erasure-correcting code, such as a Reed-Solomon code.

Each of the plurality of processing nodes **102** of the system **100** includes at least one host **104**, such as a processor, in communication with a plurality of disks **106** of each node **102**. In some embodiments, the host **104** includes, but is not limited to, at least one single-core or multiple-core CPU. In some embodiments, an I/O controller **108** is configured for coupling the disks **106** to the host **104**. Each node **102** further includes local memory, such as cache memory and/or DRAM memory. Each node **102** further includes a respective set of one or more disks **106**, such as hard disk drives and/or solid-state disks. Each node **102** further includes an inter-node communication mechanism communicatively coupling the nodes via the inter-node communication network **116**, such as a network interface card or any other components present in networked processing systems known to the art.

In some embodiments, the host **104** includes one or more multi-core x86-architecture CPU chips. In some embodiments, the I/O controller **108** includes a Raid-On-Chip controller (ROC), and the host **104** is coupled to the I/O controller **108** via a PCIe interconnect. In some embodiments, the one or more disk drives **106** include one or more SAS and/or SATA hard disk drives. In some embodiments, the one or more disk drives **106** include one or more solid-state disk drives. In some embodiments, the inter-node communication mechanism is integrated into the I/O controller **108**. For example, a ROC provides SAS and/or SATA connectivity to both local disks **106** and, via a SAS fabric, to disks **106** of other processing nodes **102**.

Each processing node **102** further includes a respective intra-node redundancy computation unit **110** configured to determine redundant data for protection of data stored in the disks **106** of the node **102**. Each processing node **102** further includes a respective delta redundancy computation unit **112** configured to determine delta data used locally by the intra-node redundancy computation unit **110** and/or sent to other nodes **102** in response to a write of data stored in the disks **106** of the node **102**. Each processing node **102** further includes an inter-node redundancy computation unit **114** configured to determine redundant data for protection of data stored in the disks **106** of other the nodes **102**.

In some embodiments, one or more of the redundancy computation units **110**, **112**, and **114** are combined into a single mechanism and/or share one or more components. For example, the redundancy computation units **110**, **112**, and **114** are, according to various embodiments, embodied in separate or combined hardware, software, and/or firmware modules, such as one or more electronic circuits or program instructions executed from carrier media by at least one processor. In some embodiments, the controller **108** includes one or more of the redundancy computation units **110**, **112**, and **114** and/or is configured to perform one or more functions of the redundancy computation units **110**, **112**, and **114**.

In some embodiments, a first intra-node protection mechanism (e.g., RAID-5) protects a first subset of the disks **106** of a first processing node **102**A, and a second intra-node protection mechanism different from the first intra-node protection mechanism (e.g., RAID-6) protects a second subset of the disks **106** of the first processing node **102**A. In further embodiments, the first subset of the disks **106** is of a different type than the second subset of the disks **106**. For example, the first subset of the disks **106** may include one or more HDDs, and the second subset of the disks **106** may include one or more SSDs. In some embodiments, a first inter-node protection mechanism provides inter-node protection for disks **106** of the first subset of the disks **106**, and a second inter-node protection mechanism (different from the first inter-node protection mechanism) provides inter-node protection for disks **106** of the second subset of the disks **106**.

In some embodiments and/or usage scenarios, two or more disks **106** of one of the processing nodes **102** are protected by a same codeword of an inter-node protection mechanism **114**. In other embodiments and/or usage scenarios, no more than one of the disks **106** of any of the processing nodes **102** is in a same codeword of an inter-node protection mechanism **114**.

In some embodiments, a write of data by the host **104**A of a first processing node **102**A to one of the disks **106** of the first processing node **104**A causes an update of first local (i.e. intra-node) redundant data stored in other disks **106** of the first processing node **102**A. The host data write also causes an update of global (i.e. inter-node) redundant data stored in at least some of the disks **106** of a second processing node **102**B. In some embodiments, the update of the global redundant data causes an update of second local redundant data stored in other disks of the second processing node **102**B. In some embodiments, the host data write is acknowledged subsequent to the update of global redundant data reaching a point of safety, such as when the host data write is recoverable even if the first processing node **102**A fails.

FIGS. **2** and **3** respectively illustrate a method **200** of processing a data write and a method **300** of processing delta data to provide scalable storage protection. System **100** is a manifestation of methods **200** and **300** and all steps or features described with regard to embodiments of system **100** or methods **200** or **300** are applicable to both the system **100** and methods **200** and **300**. However, it is noted herein that one or more steps of methods **200** or **300** may be executed via other means known to the art. Embodiments of system **100** described herein should not be interpreted to limit methods **200** or **300** in any way.

At step **202**, data is written to a selected logical block address (LBA) by a host **104**A of a first processing node **102**A. At step **204**, at least one destination disk **106** of the first processing node **102**A storing data of the selected LBA and one or more redundant disks **106** of the first processing node **102**A storing intra-node protection data for the destination disk **106** are determined. In some embodiments, the destination and intra-node redundant disks **106** are determined by at least one of the host **104**A and the controller **108**A of the first processing node **102**A. For example, driver software executing on the host **104**A of the first processing node **102**A determines the destination disk **106**, and the controller **108**A determines the redundant disks **106**. At step **206**, one or more redundant processing nodes **102** storing inter-node protection data for the destination disk **106** are determined by at least one of the host **104**A and the controller **108**A of the first processing node **102**A.

At step **208**, old data is read from the destination disk **106** at the selected LBA. At step **212**, new data of the host data write is written to the destination disk **106** at the selected LBA. At step **210**, the delta computation unit **112**A of the first processing node **102**A determines delta data utilizing the new data and the old data. At step **214**, the intra-node redundancy computation unit **110**A of the first processing node **102**A updates first redundant data stored on the redundant disks **106** of the first processing node **102**A according to the delta data.

At step **216**, the first processing node **102**A sends the delta data to at least one redundant processing node **102**, such as a second processing node **102**B different from the first processing node **102**A. Referring to FIG. **3**, the second processing node **102**B receives the delta data at step **302**, and stores the delta data in the disk cache of the second processing node **102**B at step **304**. Once the delta data is stored in the disk cache, at step **306**, the second processing node **102**B is configured to acknowledge completion of the delta data write to the first processing node **102**A. At this point, the second processing node is able to participate in recovery of the data written to the selected LBA by the host **104**A of the first processing node **102**A, if the first processing node **102**A were to fail. At step **218**, a determination is made that all of the redundant nodes **102** have acknowledged completion of the delta data writes. At step **220**, the completion of the host data write is acknowledged to the host **104**A of the first processing node **102**A.

At step **308**, subsequent to storing the delta data in the disk cache of the second processing node **102**B, delta data is selectively flushed from the disk cache. In some embodiments, such as where the disk cache is small, step **308** is performed relatively quickly, as compared to other embodiments with a larger disk cache that use algorithms such as least-recently used to determine when to flush. At step **310**, in response to flushing or making a determination to flush the delta data from the disk cache, one or more inter-node redundancy disks **106** of the second processing node **102**B storing the inter-node protection data corresponding to the delta data and one or more redundant disks **106** of the second processing node **102**B storing intra-node protection data for the inter-node redundancy disks **106** are determined by at least one of the host **104**B and the controller **108**B of the second processing node **102**B.

At step **312**, the inter-node redundancy computation unit **114**B of the second processing node **102**B updates global redundant data stored on the inter-node redundancy disks **106** of the second processing node **102**B according to the delta data. At step **314**, the intra-node redundancy computation unit **1106** of the second processing node **102**B updates second local redundant data stored on the redundant disks **106** of the second processing node **102**B according to the update of the inter-node redundancy disks **106**. At step **316**, the delta data is removed from the disk cache of the second processing node **102**B. In some embodiments, such as where the disk cache is volatile, step **306** is delayed until after one or more of step **312** and/or step **314** to ensure that the delta data is non-volatilely stored.

In some embodiments, delta data shipped between nodes **102** for computation of global redundant data is a function of old data (prior to a write of data by a host **104**) and new data written by the host **104**. In some embodiments, delta data is determined utilizing an XOR function or an XNOR function of old data and new data written by the host **104**. In other embodiments, delta data includes the old data and the new data, and both old and new data are shipped between nodes **102**. In some embodiments, delta data further includes at least one of: an indication of which node generated the delta data; a position within an inter-node protection codeword of a write that caused the delta data to be generated; and other information associated with an origin and/or a position of the delta data.

In some embodiments, inter-node redundancy computation is performed independently on each of one or more nodes **102** storing a portion of the global redundant data. For example, with a RAID-6 coding type using a two-erasure-correcting Reed-Solomon code, delta data is sent to each of two processing nodes **102** storing a portion of the global redundant data, and each of the two processing nodes **102** independently updates a portion of the global redundant data. For a two-erasure-correcting Reed-Solomon code, a position of the delta data within a codeword of the Reed-Solomon code is sent with the delta data, and each of the two processing nodes **102** is configured to independently compute an update to a portion of the global redundant data by determining a corresponding update to a portion of a remainder obtained when data in the position of the delta data within the codeword is divided by a generator polynomial of the Reed-Solomon code.

In some embodiments, delta data is reduced and/or combined locally prior to shipping to others of the nodes for computation of global redundant data. In a first example, a first write of data by the host of a first one of the processing nodes and a second write of data by the host of the first processing node are to a same LBA, and a single delta data is shipped corresponding to both of the first write and the second write. For example, where the function is an XOR, the delta data corresponds to old data (prior to the first write) XORed with second (final) data of the second write. In a second example, a codeword of an inter-node protection mechanism covers two or more disks stored on a first one of the processing nodes, and a write to more than one of the two or more disks causes a single delta data corresponding to the write to be created. Depending on a coding type of the inter-node protection mechanism and a specified reliability, a size of the delta data is equal to a size of the write to just one of the two or more disks.

In some embodiments, a host data write of a first processing node **102**A generates a plurality of different delta datas, each to be sent to a corresponding processing node **102** storing a portion of the global redundant data. In other embodiments, a host data write of a first processing node **102**A generates a single delta data that is sent to one or more processing nodes **102** storing a portion of the global redundant data.

In some embodiments, a host data write of a first processing node **102**A is to one of the disks **106** of a second processing node **102**B different from the first processing node **102**A (i.e. a "foreign" data write). With respect to the disks **106** of the system **100**, the foreign write is performed similarly to a local write. However, data of the foreign write is shipped to the second processing node **102**B rather than staying local to the first processing node **102**A. In some embodiments, another difference is that an acknowledgment of completion of the foreign write is returned to the first processing node **102**A by the second processing node **102**B subsequent to the second processing node **102**B determining completion of any inter-node redundant writes due to the foreign write.

In some embodiments, at least some of the processing nodes **102** include a disk cache, such as a solid-state disk used as a cache. The disk cache stores one or more of: data (e.g. storage) accessed by the host **104** of the processing node **102**; data accessed by the host **104** of another processing node **102**; local redundant data of the processing node **102**; global redundant data stored on disks **106** of the processing node **102**; delta data computed by the processing node **102** and/or received from another processing node **102**; and other types of data. In some embodiments, storing delta data received from other processing nodes **102** in the disk cache enables an acknowledgement of safety of the delta data and thus of safety of the corresponding host data write prior to updating of global redundant data and/or the second local redundant data protecting the global redundant data.

In some embodiments, the disk cache of a processing node **102** is managed by one or more of: the host **104** the processing node **102**; an I/O controller **108**, such as a ROC, of the processing node; a dedicated management processor; and any combination of the foregoing.

In some embodiments, the disk cache tags delta data differently from other types of data. In some embodiments, the delta data is tagged as being both dirty and in delta format, as opposed to being able to be stored directly like non-delta dirty data. In order to flush the delta data from the disk cache of a first processing node **102**A, the inter-node redundancy computation unit **114**A of the first processing node **102**A is configured to update global redundant data stored in the disks **106** of the first processing node **102**A according to the delta data, prior to the delta data being deleted or removed from the disk cache. In some embodiments, updating the global redundant data stored in the disks **106** of the first processing node **102**A includes updating intra-node redundant data protecting the global redundant data. The intra-node redundant data stored in other disks of the first processing node **102**A is updated via the intra-node redundancy computation unit **110**A of the first processing node **102**A.

In some embodiments wherein delta data is stored in the disk cache of a processing node **102**, the processing node **102** receiving delta data performs at least a portion of the inter-node redundancy computation on the delta data prior to storing the delta data in the disk cache and stores a transformed version of the delta data in the disk cache. For example, for a multiple-erasure-correcting code, the received delta data is not in a form that is directly able to be combined into global redundant data stored in the processing node **102**. By transforming the received delta data using the inter-node redundancy computation unit **114**, the transformed delta data is able to be later combined with the global redundant data via a simpler operation, such as an XOR function. In some embodiments, storing the transformed version of the delta data in the disk cache further enables combining subsequently received delta data into the transformed version of the delta data, advantageously saving space in the disk cache. For example, with a Reed-Solomon code as the inter-node protection coding type, the delta data is transformed according to a generator polynomial of the Reed-Solomon code into an update (via XOR) to a portion of a codeword remainder stored as the global redundant data.

In some embodiments cached delta data is updated or combined in the disk cache. For example, first delta data corresponding to a first write at a selected logical block address (LBA) by a host **104**A of a first processing node **102**A is stored in the disk cache of a second processing node **102**B, and second delta data corresponding to a second write at the selected LBA is received by the second processing node **102**B. The disk cache of the second processing node **102**B is configured to update the first delta data according to the second delta data so that only a single update of the global redundant data stored in the disks **106** of the second processing node **102**B is required for both of the first write and the second write. For example, if the delta data is computed at the first processing node **102**A utilizing an XOR function, the first delta data is updated by an XOR operation with the second delta data.

In some embodiments, first delta data corresponding to a first write by the host **104**A of the first processing node **102**A to data protected by an inter-node protection codeword is stored in the disk cache of a second processing node **102**B, and second delta data corresponding to a second write to data protected by the inter-node protection codeword is received by the second processing node **102**B. The disk cache of the second processing node **102**B is configured to update the first delta data according to the second delta data so that only a single update of the global redundant data stored in the disks **106** of the second processing node **102**B is required for both of the first write and the second write.

In some embodiments, local redundant data is distributed among the disks **106** of a processing node **102** in a determined fashion, such as by a CRUSH (Controlled Replication Under Scalable Hashing) algorithm or another data distribution algorithm. In some embodiments, global redundant data is distributed among the disks **106** of two or more of the processing nodes **102** in a determined fashion, such as by the CRUSH algorithm or another data distribution algorithm. For example, a first inter-node protection codeword spans disks **106** on a first subset of the processing nodes **102**, and a second inter-node protection codeword spans disks **106** on a second subset of the processing nodes **102** different from the first subset. In some embodiments, the first subset and the second subset overlap (i.e. include a at least one processing node **102** in common).

In some embodiments, the intra-node redundancy computation unit **110** is part of and/or integrated into one or more of the disks **106**. For example, some SSDs implement a RAID-5-like or RAID-6-like redundancy mechanism protecting data stored in non-volatile memory chips of the SSD. The redundancy mechanism of the SSD is able to serve as the intra-node redundancy computation unit **110** for data stored in the SSD.

In some embodiments, the processing nodes **102** are substantially identical or similarly configured. In other embodiments, the processing nodes **102** are not all symmetric, either in number and/or configuration of the host(s) **104**, amount of the local memory, number, configuration, type, and/or capacity of the disks, or in any other parameter(s), component(s), or configuration(s).

In some embodiments, at least some of the processing nodes **102** have limited or no processing ability, and are effectively "disk-only." The disk-only processing nodes **102** participate in global redundancy computation, such as by storing a portion of the global redundancy. In some embodiments, one of the processing nodes **102** becomes disk-only due to a crash of the respective host **104**, provided that at least some storage of the disk-only processing node **102** is still globally accessible. Accordingly, foreign writes from other processing nodes **102** to storage of the disk-only processing node **102** are still able to cause delta data to be generated and transmitted, such as by a controller **108** (e.g. a ROC) of the disk-only processing node **102**.

In some embodiments, a plurality of intra-node protection mechanisms **110** and/or inter-node protection mechanisms **114** are used according to one or more of: a type and/or a reliability of the disks **106** being protected; a type of data stored in the disks **106** being protected; a probability of failure of the nodes **102** covered by a selected inter-node protection mechanism **114**; and other factors.

It should be recognized that in some embodiments the various steps described throughout the present disclosure may be carried out by a single computing system or multiple computing systems. A computing system may include, but is not limited to, a personal computing system, mainframe computing system, workstation, image computer, parallel processor, or any other device known in the art. In general, the term "computing system" is broadly defined to encompass any device having one or more processors, which execute instructions from a memory medium.

Program instructions implementing methods, such as those manifested by embodiments described herein, may be transmitted over or stored on carrier medium. The carrier medium may be a transmission medium, such as, but not limited to, a wire, cable, or wireless transmission link. The carrier medium may also include a storage medium such as, but not limited to, a read-only memory, a random access memory, a magnetic or optical disk, or a magnetic tape.

Embodiments manifesting methods described herein may include storing results in a storage medium. After the results have been stored, the results are accessible in the storage medium and used by any of the method or system embodiments described herein, formatted for display to a user, used by another software module, method, or system, etc. Furthermore, the results may be stored "permanently," "semi-permanently," temporarily, or for some period of time. For example, the storage medium may be random access memory (RAM), and the results may not necessarily persist indefinitely in the storage medium.

It is further contemplated that any embodiment of the disclosure manifested above as a system or method may include at least a portion of any other embodiment described herein. Those having skill in the art will appreciate that there are various embodiments by which systems and methods described herein can be effected, and that the implementation will vary with the context in which an embodiment of the disclosure deployed.

Furthermore, it is to be understood that the invention is defined by the appended claims. Although embodiments of this invention have been illustrated, it is apparent that various modifications may be made by those skilled in the art without departing from the scope and spirit of the disclosure.

What is claimed is:

1. A storage system, comprising:

a plurality of processing nodes in communication with one another, each processing node including:

a plurality of disks local to a respective processing node;

at least one host, the at least one host configured to write data to a first selected disk of the plurality of disks;

a local redundancy computation unit configured to determine local redundant data utilizing the data written to the first selected disk by the at least one host to establish a redundancy protection for the data written in the respective processing node, the local redundant data being stored on at least one disk of the plurality of disks;

a delta computation unit configured to determine a first delta data utilizing the data written to the first selected disk by the at least one host, the delta computation unit further configured to send the determined first delta data to at least one other processing node; and

a global redundancy computation unit configured to receive a second delta data from at least a second processing node of the plurality of processing nodes, the global redundancy computation unit further configured to determine global redundant data utilizing the received second delta data, the global redundant data establishing a redundancy protection for data contained in the at least the second processing node, the global redundant data being stored on at least one disk of the plurality of disks,

wherein the second delta data is derived from data written to a second selected disk of a plurality of disks foreign to the respective processing node.

2. The system of claim 1, wherein the local redundancy computation unit is further configured to recover the data written to the first selected disk utilizing the local redundant data when the first selected disk fails.

3. The system of claim 1, wherein the global redundancy computation unit is further configured to recover data of the at least a second processing node utilizing the global redundant data when the at least a second processing node fails, and wherein the second delta data is sent by a second local redundancy computation unit of the at least the second processing node.

4. The system of claim 1,

wherein the local redundant data is first local redundant data,

wherein the local redundancy computation unit is further configured to determine second local redundant data utilizing the global redundant data, and

wherein the second local redundant data is stored on at least one disk of the plurality of disks local to the respective processing node.

5. The system of claim 4,

wherein the local redundancy computation unit is further configured to recover the data written to the first selected disk utilizing the local redundant data when the first selected disk fails,

wherein the global redundancy computation unit is further configured to recover data of the at least the second processing node utilizing the global redundant data when the at least the second processing node fails, and

wherein the local redundancy computation unit is further configured to recover the global redundant data utilizing the second local redundant data when the at least one disk storing the global redundant data fails.

6. The system of claim 1, wherein the plurality of processing nodes includes a first set of disks of the pluralities of disks among the processing nodes protected via a first global coding type and a second set of disks of the pluralities of disks among the processing nodes protected via a second global coding type, wherein the first global coding type is different from the second global coding type.

7. The system of claim 6, wherein the first set of disks includes at least one disk of a first processing node of the plurality of processing nodes and at least one disk of a second processing node of the plurality of processing nodes.

8. The system of claim 1, wherein the local redundancy computation unit is further configured to process data utilizing a first erasure-correcting code type, wherein the global redundancy computation unit is further configured to process data utilizing a second erasure-correcting code type, and wherein the first erasure-correcting code type is different from the second erasure-correcting code type.

9. The storage system of claim 1,

wherein the local redundant data is stored on the at least one disk of the plurality of disks using local redundant data writes to the at least one disk of the plurality of disks;

wherein the at least one other processing node is configured to receive the first delta data to perform global redundant data writes; and wherein the global redundant data writes are less than the local redundant data writes.

10. A storage system, comprising:

a plurality of processing nodes in communication with one another, each processing node including:

a plurality of disks local to a respective processing node;

at least one host, the at least one host configured to write data to a first selected disk of the plurality of disks; and

a controller in communication with the plurality of disks, the controller configured to:

determine local redundant data utilizing the data written to the first selected disk to establish a redundancy protection for the data written in the respective processing node;

store the local redundant data on at least one disk of the plurality of disks;

determine a first delta data utilizing the data written to the first selected disk;

send the determined first delta data to at least one other processing node of the plurality of processing nodes;

receive a second delta data from at least a second processing node of the plurality of processing nodes, wherein the second delta data is derived from data written to a second selected disk of a plurality of disks foreign to the respective processing node;

determine global redundant data utilizing the received second delta data, the global redundant data establishing a redundancy protection for data contained in the at least the second processing node; and

store the global redundant data on at least one disk of the plurality of disks local to the respective processing node.

11. The system of claim 10, wherein the controller is further configured to:

recover the data written to the first selected disk utilizing the local redundant data when the first selected disk fails; and

recover data of the at least the second processing node utilizing the global redundant data when the at least a second processing node fails.

12. The system of claim 11,

wherein the local redundant data is first local redundant data, and

wherein the controller is further configured to:

determine second local redundant data utilizing the global redundant data;

store the second local redundant data on at least one disk of the plurality of disks local to the respective processing node; and

recover the global redundant data utilizing the second local redundant data when the at least one disk storing the global redundant data fails.

13. The system of claim 10, wherein the plurality of processing nodes includes a first set of disks of the pluralities of disks among the processing nodes protected via a first global coding type and a second set of disks of the pluralities of disks among the processing nodes protected via a second global coding type, wherein the first global coding type is different from the second global coding type.

14. The system of claim 13, wherein the first set of disks includes at least one disk of a first processing node of the plurality of processing nodes and at least one disk of a second processing node of the plurality of processing nodes.

15. The system of claim 10, wherein the controller is further configured to:

determine the local redundant data utilizing a first erasure-correcting code type; and

determine the global redundant data utilizing a second erasure-correcting code type, wherein the first erasure-correcting code type is different from the second erasure-correcting code type.

16. A method of storage protection, comprising:

writing data to a first selected disk of a plurality of disks local to a first processing node of a plurality of processing nodes, the plurality of processing nodes being in communication with one another;

determining local redundant data utilizing the data written to the first selected disk to establish a redundancy protection for the data written in the first processing node;

storing the local redundant data on at least one disk of the plurality of disks;

determining first delta data utilizing the data written to the first selected disk;

sending the first delta data to at least one other processing node;

receiving second delta data at the first processing node from at least a second processing node, wherein the second delta data is derived from data written to a second selected disk of a plurality of disks local to the at least a second processing node;

determining global redundant data utilizing the second delta data, the global redundant data establishing a redundancy protection for data contained in the at least the second processing node; and

storing the global redundant data on at least one disk of the plurality of disks local to the first processing node.

17. The method of claim 16, wherein the method further includes:

recovering the data written to the first selected disk of the first processing node utilizing the local redundant data when the first selected disk fails; and

recovering data of the at least the second processing node utilizing the global redundant data when the at least the second processing node fails.

18. The method of claim 17,

wherein the local redundant data is first local redundant data, and

wherein the method further includes:

determining second local redundant data utilizing the global redundant data;

storing the second local redundant data on at least one disk of the plurality of disks local to the first processing node; and

recovering the global redundant data utilizing the second local redundant data when the at least one disk storing the global redundant data fails.

19. The method of claim 16, wherein the method further includes:

protecting a first set of disks of the processing nodes utilizing a first global coding type; and

protecting a second set of disks of the processing nodes utilizing a second global coding type, wherein the first global coding type is different from the second global coding type.

20. The method of claim 16, wherein the plurality of disks comprises multiple sets of disks, and wherein storing the local redundant data on the at least one disk of the plurality

of disks further comprises storing redundant data proportionally to a total number of disks in each set of the multiple sets of disks, and wherein storing the global redundant data on at least one disk of the plurality of disks local to the first processing node further comprises storing redundant data proportionally to a number of survivable node failures.

**21**. The method of claim **16**, wherein the method further includes:

determining the local redundant data utilizing a first erasure-correcting code type; and

determining the global redundant data utilizing a second erasure-correcting code type, wherein the first erasure-correcting code type is different from the second erasure-correcting code type.

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